PRELIMINARY SATURN ATMOSPHERIC DENSITY RESULTS FROM CASSINI'S FINAL PLUNGE

Dylan R. Boone; Mau Wong; Julie Bellerose; and Duane Roth;

The Cassini spacecraft made its final descent into the planet Saturn on September 15, 2017, capping a twenty year mission full of scientific discoveries. The high-gain antenna was held on Earth-point until torques from atmospheric drag caused the spacecraft to lose line-of-sight lock with Earth. The Doppler data collected during the final plunge contains information about the spacecraft's acceleration due to atmospheric drag, and therefore, the density of Saturn's atmosphere. In this work, we present preliminary analysis of the end of mission Doppler data and its implications regarding the density of Saturn's upper atmosphere. A reconstruction of the spacecraft's final trajectory is discussed and used to fit a model of Saturn's atmosphere to the Doppler data taken during the final plunge. The Cassini navigation team's experience flying the spacecraft through the final five low altitude Saturn periapses is also discussed in the context of atmospheric drag and density models.

INTRODUCTION

The Cassini-Huygens mission to Saturn launched in 1997, arrived at Saturn in 2004 after a seven year interplanetary cruise, deployed the Huygens probe into Titan's atmosphere upon arrival, and toured Saturn's moon system until September 2017. Exploration of the Saturn system was driven by gravitational assist flybys of the moon Titan. The final Titan flyby T126 put the spacecraft on a series of ring-grazing orbits in the summer of 2017 and a final distant, untargeted flyby of Titan enabled a ballistic impacting trajectory for Cassini's Grand Finale. The design and experience of flying these Grand Finale orbits are detailed in other sources. The focus of this work is Cassini's final plunge into Saturn's atmosphere at the end of its mission. This plunge was the culmination of the Proximal Orbits colored red in Figure 1 below. Since Saturn was experiencing northern summer, the targeted impact point was chosen just north of the equator to provide a line-of-sight radio link to Earth. Prior to the disposal of the spacecraft in Saturn's atmosphere, five close Saturn periapses between the rings and atmosphere of Saturn provided information on the overall atmospheric density of Saturn, which was used to update the predicted drag profile for the final plunge.

This work discusses the models and methods used to characterize and estimate the atmospheric density profile of Saturn. A least-squares orbit determination (OD) filter is used to estimate correc-

^{*}Cassini Orbit Determination Analyst, MD/Nav Section, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr, Pasadena, CA, 91109.

[†]Cassini Maneuver Analyst, MD/Nav Section, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr, Pasadena, CA, 91109.

[‡]Cassini Orbit Determination Lead, MD/Nav Section, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr, Pasadena, CA, 91109.

[§]Cassini Navigation Team Chief, MD/Nav Section, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr, Pasadena, CA, 91109.

tions to a nominal Saturn exponential atmosphere by minimizing the difference between observed and computed two-way coherent Doppler data collected during Cassini's descent into the atmosphere. Reaction Control Subsystem (RCS) thrusters were used to compensate for atmospheric torque and maintain the Earth-pointed attitude of the High Gain Antenna until saturated at 100% duty-cycle, at which point the data link with Earth was lost. The spacecraft then began to tumble and eventually burn up and become a part of Saturn's atmosphere. Telemetry information describing the RCS thruster firing is incorporated into the OD filter and corrections to the spacecraft initial state and Saturn zonal harmonic gravity coefficients are computed simultaneously with the estimate of atmospheric density.

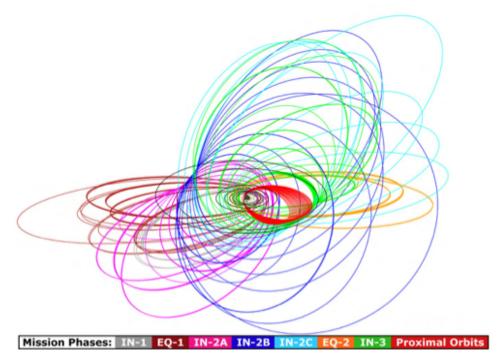


Figure 1. Saturn-centered trajectory for Cassini's Grand Finale phase

ATMOSPHERIC DENSITY MODEL

The acceleration due to atmospheric drag is given by Equation 1:

$$\boldsymbol{a}_D = -\frac{\rho C_d A V^2}{2m} \hat{\boldsymbol{V}} \tag{1}$$

where ρ is the atmospheric density at the current spacecraft location, C_D is the coefficient of drag for the spacecraft, A is the cross-sectional area of the spacecraft perpendicular to the body-relative velocity vector, m is the spacecraft mass, and \hat{V} is the unit velocity vector. The drag coefficient has a fixed value of 2.1 for Cassini and the most up to date spacecraft mass based on propellant usage is used. Cassini's High Gain Antenna (HGA) is aligned with the spacecraft Z-axis and is pointed at Earth to enable radio tracking during the flyby. The area seen by the atmosphere corresponding to the nominal Earth-pointed attitude through the plunge and is set to the Attitude and Articulation Control Subsystem (AACS) value of 20.5 m². Since the atmospheric density, drag coefficient, area,

and mass of the spacecraft appear as a product in the acceleration formula, only one of those scalar quantities can be estimated independent of the others. For this analysis, we focus on extracting density information and hold the other quantities fixed.

There are two models used to describe Saturn's atmospheric density here, one for prediction and one for estimation. The first is a project density model based on atmospheric star occultation data used for planning Cassini's final orbits. This model's prediction is updated based on the last five revolutions of Saturn prior to atmospheric disposal. The model used for estimating corrections to the density profile is an approximation of the project model using a layered, altitude-dependent exponential atmosphere. This allows estimation of base densities for each layer at break points defined by the accumulated acceleration due to drag.

A priori Atmospheric Density Model

The project density model is based on the work in Koskinen et al.² delivered to the navigation team by Darrell Strobel, and has a dependence on radial altitude with respect to Saturn r and plane-tocentric latitude θ . The formula in Equation 2 gives a number density of H_2 molecules in Saturn's atmosphere with constants given in Table 1. This is converted to a mass density using the molar weight of hydrogen molecules. The second exponential term is for coverage of the lower altitude regime.

$$n\left(r,\theta\right) = n_0 \cdot e^{\lambda_0 \left(\frac{R_t}{r} - 1\right)} \cdot e^{-43\sin\left(\frac{\theta^2}{\Delta\theta^2}\right)} + 0.1n_0 \cdot e^{-\left(\frac{r - R_t}{H}\right)} \cdot e^{-200\sin\left(\frac{\theta^2}{\Delta\theta^2}\right)}$$
(2)

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Parameter	Symbol	Units	Value
Number Density (Output)	n	cm^{-3}	
Radius (Input)	r	km	
Latitude (Input)	θ	rad	
Reference Number Density	n_0	cm^{-3}	1.26e10
Unitless Constant	λ_0		352.1
Altitudinal Constant	Н	km	65
Reference Radius	R_t	km	61700
Latitudinal Constant	$\Delta \theta$	rad	1.05

Table 1. 2017 Cassini Project Saturn Atmosphere Model

This model was used in planning the trajectory for the Grand Finale and serves as the basis for further analysis.

Exponential Atmosphere Estimation Density Model

In order to examine finer variation of atmospheric density with altitude, a layered, exponential atmospheric profile is implemented in NASA JPL's Monte software.³ This density-driven profile allows estimation of a base density for each layer, defined with altitude by the user. The density at a given point ρ is given by Equation 3 where the subscript "i" stands for the characteristics of the base of the layer in altitude h and scale height H. The scale height in Equation 4 is computed such that continuity is enforced at the layer boundaries.

$$\rho = \rho_i \exp\left(\frac{h_i - h}{H_i}\right) \tag{3}$$

$$H_{i} = \frac{h_{i} - h_{i+1}}{\log(\rho_{i+1}/\rho_{i})} \tag{4}$$

A priori base densities are taken from the project model and implemented in the layered exponential profile. Initially, the estimation model is a very close approximation of the project model. Corrections to the base densities are computed from the drag acceleration information present in the Doppler data collected during Cassini's plunge into the atmosphere. Layers are defined such that the accumulated acceleration due to drag in each layer is at least ten times the noise in the Doppler data residuals. This is similar to the methodology used in analyzing the density of Titan's atmosphere in Boone, except there is no outbound portion of the flyby. The choice of *a priori* values for the base densities is an iterative process. The initial values were taken from the project model at the chosen altitude break points and 100% uncertainty applied to those values in the estimation. After a series of initial fits, the *a priori* values equal to the uncertainties in Table 2 were chosen. The following section details the inputs to the orbit determination filter.

ORBIT DETERMINATION PROCESS

The methodology of orbit determination is used to determine Saturn's atmospheric density by extracting dynamical information from two-way radiometric tracking data collected by NASA's Deep Space Network during Cassini's final encounter with Saturn's atmosphere. The Cassini Navigation Team uses an epoch-state Kalman filter implemented in JPL's Monte software to estimate the spacecraft's trajectory in around Saturn as well as other relevant parameters such as Saturn's extended spherical harmonic gravity field. This section describes the data used, the forces modeled, and the parameters estimated and considered in this experiment.

Data arc

The traditional OD arc for Cassini spans from the apoapsis before one Titan flyby to the apoapsis after a second flyby. In the proximal mission after T126, this was modified to include several Saturn periapsis encounters or "revs". For this analysis, we focus on the final plunge of Cassini into Saturn atmosphere and begin at the apoapsis prior to Cassini's final descent. This arc starts on 12-SEP-2017 12:00 ET and the integration ends just past the final received Doppler point at 15-SEP-2017 10:35 ET. The time system used is ephemeris time (ET) which is Universal Coordinated time (UTC) kept at the spacecraft. Several tracks of sixty-second compression Doppler data anchor the epoch state of the spacecraft and one-second compression time Doppler data is taken once the atmospheric drag begins to affect the spacecraft. The data is weighted at 1xRMS of the Doppler residuals for both compression rates, with the one-second data exhibiting more noise than the sixty-second data by a factor of $1/\sqrt{\Delta t}$. Range data is not used for this study as the incoming spacecraft trajectory is well known and the dynamic information regarding the atmosphere is contained in the Doppler.

Force Modeling

The dynamic models used in this analysis were updated using estimates from the final five Saturn periapses where Cassini flew between Saturn's rings and atmosphere. A reconstruction of the arc containing the last five revs produced updates to the *a priori* values and covariance of the zonal harmonic gravity field of Saturn for degrees two through eight. The Saturn GM value was taken from the Cassini trajectory reconstruction which included the final targeted Titan flyby T126, since the satellite system GMs and ephemerides are estimated as a set. These values are corrections to the

SAT389 ephemeris computed during operations.⁵ A final full mission reconstruction of the satellite ephemerides and GM values is forthcoming from JPL's Solar System Dynamics Group. Cassini's reaction wheels were spun down prior to entering the atmosphere to enable attitude control on RCS thrusters. The reaction torque supplied by the thrusters for this momentum dumping event is modeled as an impulsive burn using spacecraft telemetry. After spin-down, the thrusters fire to counteract atmospheric drag torque on the spacecraft to maintain Earth-point and allow a two-way coherent data link until the thrusters reach 100% duty cycle and pointing can no longer be controlled. Figure 2 shows the prediction in blue and the telemetry magnitude values in red for the RCS thrusting during the final atmospheric encounter.

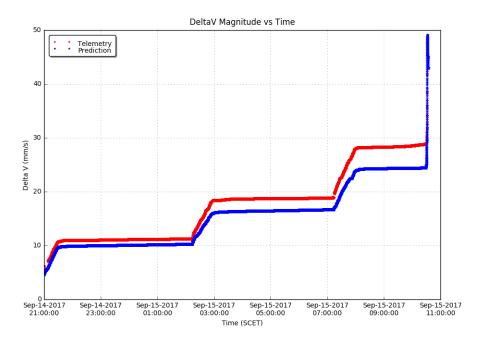


Figure 2. RCS thruster firing magnitude, telemetry vs. prediction

This prediction was informed by the experience during the last five revs around Saturn where the Cassini experienced greater drag force than the initial project model predicted. Even considering the update, the telemetered magnitude values were about 5 mm/s greater than predicted at the time that the thruster duty cycles reached 100%. The thruster firing is accumulated into batches and modeled as a constant acceleration over the batch size in the OD filter. Stochastic accelerations are estimated to account for mis-modeling in the thruster profile, Radioisotope Thermoelectric Generator (RTG) heat re-radiation, or other unmodeled dynamics.

Filter Setup

A simplified of the Cassini Navigation Team's orbit determination filter is used to estimate corrections to the layered base density model of Saturn's atmosphere. The number of parameters included is kept intentionally minimal to prevent dilution of the information content in the drag signal. Table 2 lists the parameters included in the orbit determination solution, both estimated parameters which have corrections computed and consider parameters whose values are fixed but whose uncertainty affects the resulting estimated error covariance. The spacecraft epoch state at the start of the arc is

estimated, along with corrections to the base density values and Saturn zonal harmonic gravity coefficients to degree eight. The gravity terms estimated are consistent with the most recently accepted project gravity model and are have updated *a priori* values taken from a reconstruction of Cassini's trajectory through the last five revs. The consider parameters are standard for using Earth-based radiometric tracking data. A drag scale factor is considered at the level of 5% of the drag coefficient to account for potential errors in the fixed values of the drag coefficient, projected cross-sectional spacecraft area, and spacecraft mass. The 1σ uncertainties assigned to the base densities are 100% of the *a priori* nominal values.

Table 2. Filter parameter setup

Parameter	Unit	Estimated/Considered	a priori σ
Epoch state S/C position - X/Y/Z	km	Estimated	0.46/0.08/0.03
Epoch state S/C velocity - X/Y/Z	mm/s	Estimated	0.52/0.14/0.49
Inbound Density Layer [0]	kg/km ³	Estimated	2.44E-01
Inbound Density Layer [1]	kg/km ³	Estimated	1.93E-01
Inbound Density Layer [2]	kg/km ³	Estimated	1.52E-01
Inbound Density Layer [3]	kg/km ³	Estimated	1.07E-01
Saturn gravity zonal harmonics	unitless	Estimated	Reconstructed values
Earth pole motion - X/Y	deg	Considered	8.594E-07
UT1 bias	sec	Considered	2.5E-04
DSN station locations	km/deg	Considered	2003 covariance ⁶
Troposphere path delay - wet/dry	km	Considered	1.0E-05/1.0E-05
Ionosphere path delay - day/night	km	Considered	5.5E-04/1.5E-04
Drag scale factor	unitless	Considered	0.105

ESTIMATION RESULTS

In an orbit determination solution run, the equations of motion are numerically integrated to produce a spacecraft trajectory, the Doppler data is processed and the difference between the observed and computed frequencies, and the residual values are accumulated and used to compute a correction to the desired state vector. This process is iterated to convergence, defined as some threshold of change in the postfit residuals between iterations. Figure 3 shows the prefit observed minus computed Doppler residuals, where no change has been made to the *a priori* states. The time system is Earth Receive Time UTC, which is approximately 83 minutes after events occur at the spacecraft due to one-way light time travel. About 50 mm/s of unmodeled drag signature is present in the prefit residuals, which the estimation procedure will flatten by adjusting the spacecraft state and atmospheric base densities. The majority of this data is at a sixty-second compressions rate, with the final ten minutes of data compressed at a one-second rate to better resolve variations in the atmospheric density.

Figure 4 shows the postfit residuals form the second iteration of the OD process, with corrections applied to the estimated states and a new trajectory integrated using the updated force models. The one-second data taken while Cassini descended into the atmosphere is fit an RMS of less than 1 mm/s. There is some signature in the residuals at the 0.5 mm/s level prior to the plunge that is likely due to the low frequency batching of the accelerations used to model thruster firing. The thruster firing model is based on spacecraft telemetry and is not estimated in the filter.

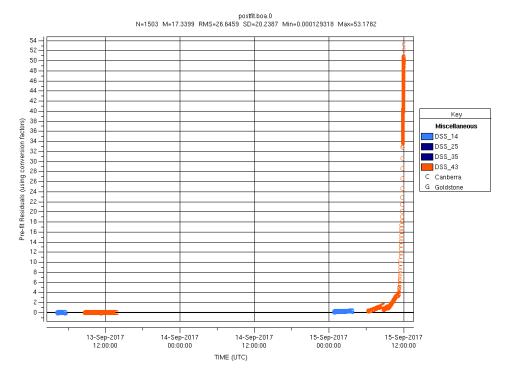


Figure 3. Prefit residuals for initial OD fit (mm/s)

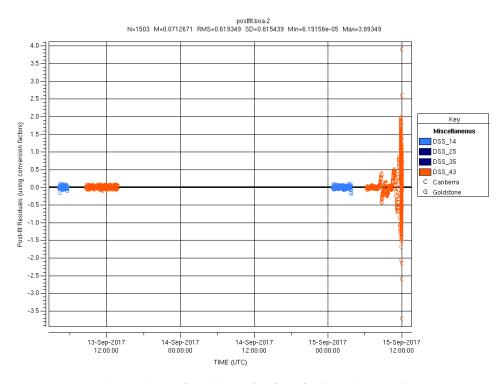


Figure 4. Postfit residuals for final OD iteration (mm/s)

Table 3 shows the iterated corrections to the atmospheric base densities estimated in the OD process along with their 1σ uncertainties. The altitudes were selected such that the accumulated drag signature in each layer was at least ten times the noise in the Doppler residuals. Additional layers above 1436 km do not have sufficient data strength to compute a meaningful correction; the filter does not reduce the *a priori* uncertainty in this regime. Similarly, there are a few Doppler points remaining that were collected while the spacecraft was below 1304 km, but the noise in the data grows as the High Gain Antenna was on the verge of being torqued off Earth-point.

Table 3. Base density layer estimation results

Base altitude (km)	Base Density (kg/km ³)	1σ uncertainty (kg/km ³)	Scale Height (km)
1304.4	2.59E-01	1.06E-01	418
1341.6 1379.3	2.11E-01 1.68E-01	9.44E-02 7.42E-02	381 383
1436.6	1.19E-01	5.77E-02	200

Corrections to the Saturn gravity zonal harmonics were less than half-sigma level since the *a priori* values were updated based on data from the last five revs about Saturn. Differences in the integrated spacecraft trajectory between the final operations solution and the solution including atmospheric density estimation was about 200 meters. Figure 5 shows the variation of atmospheric drag acceleration with spacecraft distance from Saturn during the final ten minutes of Cassini's life.

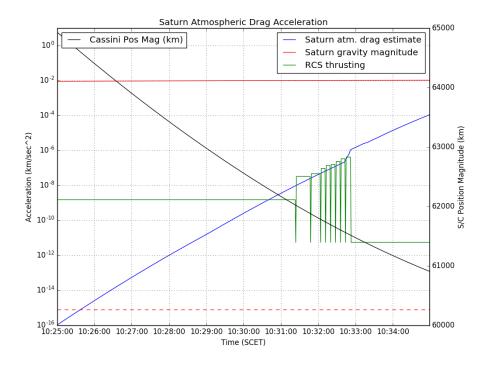


Figure 5. Saturn atmospheric drag at final plunge

The dotted red line near the x-axis represents the 1-bar surface radius of Saturn. The green steps plotted show the constant acceleration batches that model RCS thrusting to counteract atmospheric

drag torque. The acceleration due to drag remains two orders of magnitude below Saturn's gravitational acceleration during the regime where tracking data is collected. Yet, the strength of the Doppler is sufficient to reduce the uncertainty in the base density layers to 40-50% of the estimated value. Each layer in this analysis accumulates only single digit numbers of Doppler points at one-second compression. The time frame between sensing Saturn's atmosphere and losing HGA-to-Earth pointing is a very short time frame of only minutes. A similar experiment estimating Titan's atmosphere from the T107 flyby accumulated 25 minutes of data and resulted in uncertainties of 10-25% of the estimated density values.⁴

COMPARISON TO RESULTS FROM OTHER SOURCES

During the last five revs (288-292) priori to atmospheric entry, the Navigation Team estimated corrections to the spacecraft drag coefficient C_D using data before and after periapsis to constrain the amount of experienced drag. There was no tracking data during these five Saturn periapses, so no estimation of densities is possible. The estimation of C_D acts as a scaling factor and the results from the last five revs are shown in Table 4. The C_D estimates during the last five revs show that the densities encountered were on the order of 250% of the nominal project density model. This data combined with thruster duty cycle performance allowed Mission Planning and AACS to produce an updated expected nominal atmosphere for the final plunge. The updated predict also takes into account the different frontal cross-sectional areas produced by the spacecraft attitude in the last five revs.

Table 4. C_D estimates from last five revs

Rev number	C_D estimate	1σ uncertainty	% of nominal atmosphere
288	5.42	0.24	258
289	5.76	0.17	274
290	4.84	0.12	230
291	5.34	0.18	254
292	4.98	0.20	237

The Ion and Neutral Mass Spectrometer (INMS) instrument took particle count readings through the last five revs of Cassini's trajectory as well as during the final plunge. The INMS team has generously shared their data for the plunge⁸ with the Navigation Team and their results along with the OD estimates are compared to the updated predicted atmosphere in Figure 6. The data points are plotted along with their corresponding 1σ error bars. The error bars on the NAV densities encompass the updated project model predict curve and the INMS data points are within the NAV 1σ level for the highest altitude two base density layers. The INMS instrument uses a calibration factor based on data from previous Navigation solutions and agrees with the NAV solution at the 2σ level. The INMS data does not extend to the two lowest altitude NAV density layers since about a minute's worth of Doppler tracking continued once the spacecraft could no longer return telemetry. The Cassini AACS team is currently working on adapting their torque-based atmospheric density estimation methods to the final plunge, which will provide another point of comparison for these results.

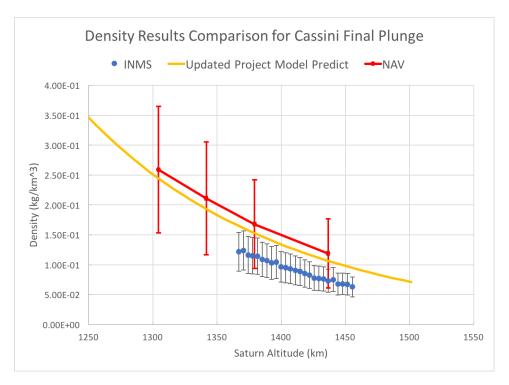


Figure 6. Comparison between density results from NAV, INMS, and project models

CONCLUSION

This work showcases the final opportunity for the Cassini navigation team to estimate a density profile for Saturn's upper atmosphere using Doppler tracking data from the spacecraft's last moments. Doppler tracking data at a one-second compression rate is collected during the last ten minutes of the mission and fit using refined Saturn gravity zonal harmonics to produce estimates of base density layers in an exponential atmosphere model. These density estimates are corrections to a project density model updated based on experience in Cassini's last five revolutions about Saturn prior to atmospheric descent. A least squares filter is employed to simultaneously correct the spacecraft trajectory, the Saturn gravity field, and density of Saturn's upper atmosphere. The residuals in the Doppler data are fit to an RMS of less than 1 mm/s. The drag signal present in the Doppler data reduces the 1σ uncertainty in the base density layers from 100% to around 50%. The NAV estimate of atmospheric density is within 1σ of density estimates from the INMS instrument for the altitudes where data overlaps. The NAV density estimates are slightly higher than the updated project model's prediction coming into the plunge. Potential refinements to the analysis include using a full-mission reconstructed Saturn gravity field, modeling thruster firing in smaller batches, and revisiting the NAV-derived scale factor applied to INMS measurements. However, the drag information in the Doppler data is strong, changes to the OD force modeling or a priori density values produced only small changes in the final estimates. While our spacecraft is gone, the data returned by Cassini will continue to enable new discoveries for years to come and inspire the next generation of scientists and engineers.

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